

# Could SXP 1062 be an Accreting Magnetar?

Lei Fu<sup>1,2</sup> and Xiang-Dong Li<sup>1,2</sup>

<sup>1</sup>*Department of Astronomy, Nanjing University, Nanjing 210093, China*

<sup>2</sup>*Key laboratory of Modern Astronomy and Astrophysics, Ministry of Education, Nanjing 210093, China*

## ABSTRACT

In this work we explore the possible evolutionary track of the neutron star in the newly discovered Be/X-ray binary SXP 1062, which is believed to be the first X-ray pulsar associated with a supernova remnant. Although no cyclotron feature has been detected to indicate the strength of the neutron star's magnetic field, we show that it may be  $\gtrsim 10^{14}$  G. If so SXP 1062 may belong to the accreting magnetars in binary systems. We attempt to reconcile the short age and long spin period of the pulsar taking account of different initial parameters and spin-down mechanisms of the neutron star. Our calculated results show that, to spin down to a period  $\sim 1000$  s within  $10 - 40$  kyr requires efficient propeller mechanisms. In particular, the model for angular momentum loss under energy conservation seems to be ruled out.

*Subject headings:* stars: neutron – X-rays: binaries: SXP 1062

## 1. Introduction

As a subgroup of high-mass X-ray binaries (HMXBs), Be/X-ray binaries (BeXBs) consist of a neutron star (NS) and a Be companion star which show emission lines and infrared (IR) excess in its spectrum. The origin of the emission lines and the IR excess is attributed to the circumstellar discs, which is fed from the material expelled from the rapidly rotating Be stars. The X-ray emissions is believed to originate from accretion of matter in the circumstellar discs by the NSs (see Reig 2011, for a review).

BeXBs are subdivided into persistent and transient sources according to their different X-ray properties. Transient systems are characterized by outbursting activities, in which the X-ray flux increases by  $\sim 1 - 4$  orders of magnitude compared with in quiescent state, and the outbursts typically last about  $0.2 - 0.3$  orbital period. These systems often have

moderately eccentric ( $e \gtrsim 0.3$ ) and relatively narrow orbits ( $P_{\text{orb}} \lesssim 100$  days). Persistent sources are relatively quiet systems with low X-ray luminosities ( $L_X \sim 10^{34} - 10^{35} \text{ erg s}^{-1}$ ), the variability of which is less than an order of magnitude. They usually have slowly rotating NSs ( $P \gtrsim 200$  s), low eccentric ( $e \lesssim 0.2$ ) and relatively wide orbits ( $P_{\text{orb}} \gtrsim 200$  days) (Reig 2011).

Recently Hénault-Brunet et al. (2012) reported a new BeXB SXP 1062 in the Wing of the Small Magellanic Cloud (SMC). This source was first discovered as a transient BeXB during the *XMM-Newton* and *Chandra* observations in 2010, and was not active during the *ROSAT* and *ASCA* observations of the SMC (Haberl et al. 2000; Yokogawa et al. 2003). However, SXP 1062 seems to share some characteristics with persistent BeXBs: a relatively low intrinsic X-ray luminosity  $L_X \simeq 6.3^{(+0.7)}_{(-0.8)} \times 10^{35} \text{ erg s}^{-1}$  (corresponding an accretion rate of  $\dot{M} = L_X/\eta c^2 \sim 6 \times 10^{15} \text{ g s}^{-1}$  with energy conversion efficiency  $\eta = 0.1$ ,  $c$  is the speed of light), a slowly rotating NS with period of  $P \simeq 1062$  s, a relatively flat light curve with sporadic fluctuation less than an order of magnitude, and a probably wide orbital period  $P_{\text{orb}} \sim 300$  days derived from the Corbet (1984) diagram. What makes this discovery most noticeable is that SXP 1062 is located in the center of a shell-like nebula, which is considered to be a supernova remnant (SNR), aging only  $\sim 10 - 40$  kyr (Haberl et al. 2012; Hénault-Brunet et al. 2012). Thus SXP 1062 provides the first example of an X-ray pulsar associated with a SNR, and it challenges the traditional spin-down model of NSs because of its extraordinarily long spin period combined with a relatively young age.

Haberl et al. (2012) measured the spin period change in SXP 1062 over a 18 day duration of observation. Their timing analysis shows that the NS in SXP 1062 has a very large average spin-down rate with the spin frequency derivative  $\dot{\nu} \sim 2.6 \times 10^{-12} \text{ Hz s}^{-1}$  (or period derivative  $\dot{P} \sim 100 \text{ s yr}^{-1}$ ). If the NS has a normal magnetic field ( $B \sim 10^{12} - 10^{13} \text{ G}$ ), it's hard to spin-down to a period  $\sim 1000$  s within a few  $10^4$  years. Assuming in the extreme case that the NS has spun down with a constant spin frequency derivative  $-2.6 \times 10^{-12} \text{ Hz s}^{-1}$  over it's whole lifetime, Haberl et al. (2012) derived the lower limit of the initial spin period of the NS is 0.5 s. Since the duration of the observation lasts only 18 days (probable less than one tenth of the orbit period), the extraordinarily large spin-down rate is very unlikely to sustain in the whole lifetime of SXP 1062, thus the present value of spin-down rate may be just a short-term one.

Popov & Turolla (2012) (hereafter PT12) suggest another possibility to reconcile the long spin period and short age of SXP 1062. Assuming that the NS is spinning at the equilibrium period, PT12 estimated the *current* magnetic field to be  $B \lesssim 10^{13} \text{ G}$  according to the model of Shakura et al. (2012). Their calculations show that if the NS in SXP 1062 was born as a magnetar ( $B > 10^{14} \text{ G}$ ) it can be spun down to  $\sim 1000$  s within a few  $10^4$  yr.

In this work we consider the proposed mechanisms that can account for the observed rapid spin-down in SXP 1062, if it is alternatively a magnetar with current field strength  $\gtrsim 10^{14}$  G. In Section 3 we point out that this possibility remains according to current observations. Based on this, we investigate its spin-down evolution, taking account of various kinds of braking torques during the propeller stage, which is introduced in Section 2, to examine how the observations of SXP 1062 can constrain the possible spin-down mechanisms in NSs. We present our calculated results in Section 4, and discuss their possible implications in Section 5. We conclude that the spin-down evolution is sensitive to the specific propeller mechanism rather the initial spin period of the NS.

## 2. Spin-down models of NSs in HMXBs

### 2.1. The ejector phase

Normally a newborn NS in a binary first appears as a radio pulsar (or ejector) after the supernova explosion (Lipunov 1992). In this phase the spin-down of the NS is due to the loss of its rotational energy dominated by magneto-dipole radiation and the outgoing flux of relativistic particles. If the NS's companion is a high-mass star, the stellar wind matter from the companion within the gravitational radius of  $R_G = 2GM/V^2$  will be captured by the NS at a rate  $\dot{M} = \pi R_G^2 \rho V$ . Here  $G$  is the gravitational constant,  $M$  the mass of the NS,  $\rho$  the density of the wind at  $R_G$ , and  $V$  the velocity of the NS relative to the stellar wind, i.e.  $V = (V_{\text{orb}}^2 + V_w^2)^{1/2}$ , where  $V_{\text{orb}}$  and  $V_w$  are the orbital velocity of the NS and the wind velocity, respectively. The pressure of the outgoing radiation and particles is larger than that of the incoming matter at  $R_G$ . The energy loss rate can be expressed as  $\dot{E} = -\mu^2 \Omega^4 (1 + \sin^2 \alpha) / c^3$  (Spitkovsky 2006), where  $\mu \equiv BR^3$  is the magnetic moment of the NS ( $B$  and  $R$  are the surface magnetic field and radius of the NS, respectively),  $\Omega$  the angular velocity, and  $\alpha$  the inclination angle between the magnetic and rotational axes. Thus the spin-down rate in the ejector phase is

$$\dot{P} = \frac{4\pi^2 B^2 R^6 (1 + \sin^2 \alpha)}{I P c^3}, \quad (1)$$

where  $I$  is moment of inertia of the NS. As the NS spins down and the outgoing pressure goes down, the transition to the supersonic propeller phase will occur when the two pressures are in balance. The spin period of the NS at the transition point is

$$P_{\text{ej}} = \frac{2\pi}{c} \left[ \frac{B^2 R^6 (1 + \sin^2 \alpha)}{4\dot{M} V} \right]^{1/4}. \quad (2)$$

## 2.2. The propeller phase

Once the wind matter crosses the gravitational radius  $R_G$  the propeller phase starts. If the plasma enters the light cylindrical radius the pulsar mechanism will switch off and the incoming matter will form a quasi-static atmosphere surrounding the NS. At this moment accretion does not occur since the magnetosphere radius  $R_m = (\mu^2/\dot{M}\sqrt{2GM})^{2/7}$  is larger than the corotation radius  $R_{co} \equiv (GM/\Omega^2)^{1/3}$  of the NS. The infalling material is stopped at the magnetosphere by the centrifugal barrier, which prevents material from accreting onto the NS. The ejected material will carry away the angular momentum of the NS and decelerate its spin. This so-called propeller effect was first introduced by Illarionov & Sunyaev (1975).

Davies et al. (1979) pointed out that, according to the Mach number  $\mathcal{M} = \Omega R_m/c_s$  (here  $c_s \sim (GM/R_m)^{1/2}$  is the sound velocity at  $R_m$ ) at the magnetosphere, the propeller phase can be subdivided into two cases: supersonic propeller and subsonic propeller. Accordingly the above mentioned propeller mechanism is related to the supersonic propeller since the Mach number  $\mathcal{M} > 1$ . This phase ends when  $R_{co} = R_m$  (i.e.,  $\mathcal{M} = 1$ ) and the corresponding spin period

$$P_{eq} = 2^{11/14} \pi \mu^{6/7} \dot{M}^{-3/7} (GM)^{-5/7} \quad (3)$$

is called the equilibrium period. Further works (Arons & Lea 1976; Elsner & Lamb 1977) showed that, unless the material outside the magnetosphere is able to cool, accretion is unlikely to happen. Thus, even with  $R_{co} > R_m$  the propeller stage will succeed once the energy deposition rate is larger than the energy loss rate of the surrounding shell, and keep removing angular momentum from the NS. Because the Mach number  $\mathcal{M} < 1$ , this stage is called the subsonic propeller. This process will cease if the loss rate of the rotational energy can no longer support the surrounding atmosphere against cooling, then the atmosphere will collapse and the NS enters the accretor stage. The spin period of the NS at this point is so-called the break period, given by (Davies & Pringle 1981; Ikhsanov 2001)

$$P_{br} \simeq 86.88 \mu_{30}^{16/21} \dot{M}_{16}^{-5/7} (M/M_\odot)^{-4/21} \text{ s}, \quad (4)$$

where  $\mu_{30} = \mu/10^{30} \text{ G cm}^3$ , and  $\dot{M}_{16} = \dot{M}/10^{16} \text{ g s}^{-1}$ .

It should be noted that the supersonic propeller can occur in both wind-fed and disc-fed cases. However, there is no consensus on the angular momentum loss rate of a NS during the propeller phase (Davies et al. 1979). Here we adopt a general formulation of the spin-down torque as follows (Mori & Ruderman 2003),

$$I\dot{\Omega} = -\dot{M} R_m^2 \Omega_K(R_m) \left[ \frac{\Omega}{\Omega_K(R_m)} \right]^\gamma, \quad (5)$$

where  $\gamma$  is a parameter ranging from  $-1$  to  $2$ , and its value reflects various propeller mechanisms and spin-down efficiencies. For the supersonic propeller,  $\gamma = -1, 0$  and  $1$ . When

$\gamma = -1$ , the matter is assumed to be ejected with the escape velocity at  $R_m$ , i.e.,  $v_{\text{esc}}(R_m) = \sqrt{2GM/R_m}$  (Illarionov & Sunyaev 1975), and the spin-down torque is calculated based on energy budget. The energy loss rate is  $I\Omega\dot{\Omega} = -(1/2)\dot{M}v_{\text{esc}}^2(R_m) = -\dot{M}[R_m\Omega_K(R_m)]^2$ , where  $\Omega_K(R_m)$  is the Keplerian angular velocity at  $R_m$ . When  $\gamma = 0$  and 1, the matter is assumed to be ejected at the escape velocity  $v_{\text{esc}}(R_m)$  (Davidson & Ostriker 1973) and the rotating velocity  $R_m\Omega$  (Shakura 1975) of the magnetosphere at  $R_m$ , respectively, and the torque is derived under the angular momentum budget. The corresponding angular momentum loss rate is  $I\dot{\Omega} = -\dot{M}R_m(2GM/R_m)^{1/2} = -2^{1/2}\dot{M}R_m^2\Omega_K(R_m)$  and  $I\dot{\Omega} = -\dot{M}R_m^2\Omega$ , respectively. The value of  $\gamma$  for the subsonic propeller phase is 2, in which the rotational energy of the NS is assumed to be dissipated at a rate of  $I\Omega\dot{\Omega} = -\dot{M}R_m^2\Omega_K^2(R_m)[\Omega/\Omega_K(R_m)]^3$ , and the resulting torque is  $I\dot{\Omega} = -\dot{M}R_m^2\Omega_K(R_m)[\Omega/\Omega_K(R_m)]^2$ . Thus the spin-down rate in the propeller stage can be summarized as

$$\dot{P} = \frac{(2\pi)^{\gamma-1}(GM)^{\frac{1-\gamma}{2}}\dot{M}R_m^{\frac{1+3\gamma}{2}}}{IP^{\gamma-2}}. \quad (6)$$

As an illustration, we consider a  $1.4 M_\odot$  NS with an initial spin period of 0.01 s, a surface magnetic field of  $10^{12}$  G, and an accreting rate of  $10^{16}$  gs $^{-1}$ . The corresponding characteristic spin-periods are  $P_{\text{ej}} \simeq 0.24$  s,  $P_{\text{eq}} \simeq 6.7$  s and  $P_{\text{br}} \simeq 81.5$  s respectively. The timescales in the supersonic propeller phase varies from 30 kyr to 20 Myr as  $\gamma$  decreases from 1 to  $-1$ , and in the subsonic propeller phase which has a spin-down rate irrelevant with  $P$  the spin-down timescale is  $\sim 90$  kyr. In the above calculation we use  $300 \text{ km s}^{-1}$  as the relative velocity (see Raguzova & Lipunov 1998).

### 2.3. The accretor phase

Steady wind accretion onto the NS starts at  $P > P_{\text{br}}$ . In this phase the spin period could be further changed since the wind matter possesses some angular momentum. However both observations (Bildsten et al. 1997) and numerical calculations (e.g., Fryxell & Taam 1988; Matsuda et al. 1992; Azner & Börner 1995; Ruffert 1999) have shown that the efficiency of angular momentum transfer in wind accretion is quite low, with alternating short-term spin-up and spin-down. Thus one may expect that the present spin periods of wind-fed X-ray pulsars are not significantly different from the  $P_{\text{br}}$  achieved earlier.

Recently Shakura et al. (2012) proposed a model of subsonic quasi-spherical accretion onto a slowly rotating NS in HMXBs with low X-ray luminosities ( $L_X < 10^{36}$  ergs $^{-1}$ ). In this model the accreting matter settles down subsonically onto the rotating magnetosphere, forming an extended quasi-static shell around it. The angular momentum can be removed from or injected into the NS depending on the sign of the specific angular momentum of the

falling matter. In the case of moderate coupling between the plasma and the magnetosphere, from the torques acted on the NS due to both the magnetosphere-plasma interaction and accretion, the changing rate of the spin period is derived to be (see also PT12)

$$\dot{P} = -\frac{P^2}{2\pi I} \left[ A \dot{M}_{16}^{(3+2n)/11} - C \dot{M}_{16}^{3/11} \right], \quad (7)$$

where  $A \sim 2.2 \times 10^{32} K_1 (B_{12} R_6)^{1/11} V_{300}^{-4} P_{\text{orb},300}^{-1}$ , and  $C \sim 5.4 \times 10^{31} K_1 (B_{12} R_6)^{13/11} P_{1000}^{-1}$ . Here  $B_{12} = B/10^{12}$  G,  $R_6 = R/10^6$  cm,  $P_{1000} = P/1000$  s,  $P_{\text{orb},300} = P_{\text{orb}}/300$  hr,  $V_{300} = V/300$  km s $^{-1}$ . The constants  $K_1$  and  $n$  are set to be 40 and 2 respectively. It is seen that there is an critical accretion rate at which  $\dot{P} = 0$ .

### 3. Estimate of the magnetic field

The NS magnetic field is a critical parameter in the spin-down models. Before investigating the spin history of SXP 1062, we need to know the information about its magnetic field strength. The cyclotron features in the X-ray spectra provide the most direct and accurate way to measure the magnetic field strengths of accreting NSs. Unfortunately, they have not been detected in SXP 1062. Nevertheless, there are several other ways to estimate the NS magnetic field from its spin period and period derivative, though model dependent.

One of the hints comes from the young age of the SNR associated with the NS. This requires that the lifetime of the ejector phase (usually much longer than that of the propeller phase) must end within a few  $10^4$  years. Assuming that the magnetic field has changed little during this phase and that the initial spin period is much smaller than  $P_{\text{ej}}$ , one can estimate the timescale of the ejector phase to be (PT12)

$$\tau_{\text{ej}} = \frac{c^3 I P_{\text{ej}}^2}{16\pi^2 B^2 R^6} \sim 1.5 \dot{M}_{16}^{-1/2} V_{300}^{-1/2} B_{12}^{-1} \text{ Myr}. \quad (8)$$

This value is about two orders of magnitude larger than the estimated age of SXP 1062, unless  $B_{12} > 100$ . This means that SXP 1062 must have possessed very strong magnetic field.

PT12 further assumed that the NS in SXP 1062 is spinning at the equilibrium period as described in the model of Shakura et al. (2012), and derived the current magnetic field to be  $B_{12} \lesssim 10^{13}$  G using Eq. (7). Accordingly they suggest that the NS magnetic field must have been stronger in the past and then decayed to its present, normal value. It is noted that the model of Shakura et al. (2012) has quite a few parameters whose magnitudes are uncertain. For example, the value of  $K_1$ , which relates the poloidal ( $B_p$ ) and toroidal ( $B_\phi$ ) magnetic

field components, is found to be  $\sim 40$  in Shakura et al. (2012). This will result in  $B_\phi \gg B_p$  during the accretor phase, and it is not known whether the magnetic field configuration can remain stable in this case (cf. Aly 1985; Wang 1995).

The extraordinary large spin-down rate of SXP 1062 can be used to put useful constraint on the magnetic field of the NS. As shown by many authors (Lynden-Bell & Pringle 1974; Lipunov 1982; Bisnovatyi-Kogan 1991), the maximum spin-down torque exerted on a NS in either disc or spherical accretion is

$$I\dot{\Omega} = -\kappa \frac{\mu^2}{R_{\text{co}}^3}, \quad (9)$$

where  $\kappa < 1$ . To account for the spin-down rate measured in SXP 1062, the NS magnetic field has to be

$$B \simeq 3 \times 10^{14} \kappa^{-1/2} M_{1.4}^{1/2} I_{45}^{1/2} R_6^{-3} (\dot{P}/100 \text{ syr}^{-1})^{1/2} \text{ G}, \quad (10)$$

where  $M_{1.4} = M/1.4M_\odot$ , and  $I_{45} = I/10^{45} \text{ g cm}^2$ . The same result can be obtained if the spin-down torque in the subsonic propeller phase (Davies & Pringle 1981) is used.

Another efficient spin-down mechanism was proposed by Illarionov & Kompaneets (1990). They argued that there could be outflows from the NS magnetosphere caused by heating of hard X-ray emission of the NS if the X-ray luminosity falls in the range of  $\sim 2 \times 10^{34} \text{ ergs}^{-1} - 3 \times 10^{36} \text{ ergs}^{-1}$ . Compton scattering heats the accreted matter anisotropically, and some of the heated matter with a low density can flow up and form outflows to take the angular momentum away. The corresponding spin-down torque is

$$I\dot{\Omega} = -\kappa \frac{\chi}{2\pi} \dot{M}_{\text{out}} \Omega R_{\text{m}}. \quad (11)$$

Here  $\dot{M}_{\text{out}}$  is the mass outflow rate (no larger than the mass transfer rate) and  $\chi$  is the solid angle of the outflow. This gives the magnetic field to be

$$B \simeq 3.6 \times 10^{14} \left(\frac{\kappa\chi}{2\pi}\right)^{-7/8} I_{45}^{7/8} M_{1.4}^{1/4} I_{45}^{1/2} R_6^{-3} \left(\frac{\dot{M}_{\text{out}}}{10^{16} \text{ gs}^{-1}}\right)^{-3/8} \left(\frac{\dot{P}}{100 \text{ syr}^{-1}}\right)^{7/8} \left(\frac{P}{1062 \text{ s}}\right)^{-7/8} \text{ G}. \quad (12)$$

The above estimates show that SXP 1062 could be an accreting magnetar. Similar conclusions have also been drawn for other X-ray pulsars in HMXBs. Doroshenko et al. (2010) reported the spin history of the 685 s X-ray pulsar GX 301–2, and found it spinning down at a rate  $\dot{\nu} \sim 10^{-13} \text{ Hz s}^{-1}$ . Reig et al. (2012) showed that the measurements of the spin period (5560 s) of 4U2206+54 imply a spin-down rate of  $\dot{\nu} \sim -1.5(\pm 0.2) \times 10^{-14} \text{ Hz s}^{-1}$ . Using the above spin-down mechanisms to explain the spin-down rates also leads to very strong magnetic fields ( $> 10^{14} \text{ G}$ ) in these NSs (see also Lipunov 1982).

Ikhsanov & Finger (2012) suggested an alternative interpretation for the rapid spin-down in GX 301–2. They showed that if the accreting material is magnetized, the magnetic pressure in the accretion flow increases more rapidly than its ram pressure, and under certain conditions the magnetospheric radius

$$R_{\text{mca}} \simeq 1.5 \times 10^8 \alpha_{0.1}^{2/3} B_{12}^{6/13} R_6^{18/13} T_6^{-2/13} M_{1.4}^{1/13} \dot{M}_{16}^{-4/13} \text{ cm}, \quad (13)$$

is considerably smaller than the traditional magnetospheric radius. Here  $\alpha = 0.1\alpha_{0.1}$  is the efficiency parameter of Bohm diffusion, and  $T = 10^6 T_6$  K is the plasma temperature at the magnetospheric boundary. The spin-down torque applied to the NS is found to be

$$I\dot{\Omega} = -\frac{\kappa_m \mu^2}{(R_{\text{co}} R_{\text{mca}})^{3/2}}, \quad (14)$$

where  $\kappa_m$  is a dimensionless efficiency parameter for the magnetic viscosity coefficient, and  $0 < \kappa_m < 1$ . The above equation can explain the spin-down of GX 301–2 with a normal field of a few  $10^{12}$  G if  $\kappa_m \sim 0.1$ . In the case of SXP 1062, it results in the estimate of the magnetic field to be

$$B \simeq 2 \times 10^{14} \kappa_{0.1}^{-13/17} I_{45}^{13/17} M_{1.4}^{8/17} I_{45}^{13/17} R_6^{-3} \dot{M}_{16}^{-6/17} T_6^{-3/17} \left(\frac{\dot{P}}{100 \text{ yr}^{-1}}\right)^{13/17} \left(\frac{P}{1062 \text{ s}}\right)^{-13/17} \text{ G}, \quad (15)$$

where  $\kappa_{0.1} = \kappa_m/0.1$ . In the same way, Ikhsanov (2012) estimated the magnetic field of SXP 1062 to be  $\sim 4 \times 10^{13}$  G by assuming  $\kappa_m = 1$ . Even this limiting value is comparable to the quantum critical field  $B_Q = 4.4 \times 10^{13}$  G.

According to the above arguments, in the following we assume that the current magnetic field of SXP 1062 is  $\gtrsim 10^{14}$  G. As to the evolution of the magnetic field, we consider two kinds of models. First we assume that the magnetic field was initially stronger and adopt a phenomenological model for the magnetic field decay (Dall’Osso et al. 2012)

$$\frac{dB}{dt} = -AB^{1+\alpha} = -\frac{B}{\tau_d(B)}, \quad (16)$$

where the field decay timescale  $\tau_d(B) = (AB^\alpha)^{-1}$ , and  $A$  and  $\alpha$  are constants. The solution of the above equation in the case of  $\alpha \neq 0$  is

$$B = B_i (1 + \alpha t / \tau_{d,i})^{-1/\alpha}, \quad (17)$$

where  $B_i$  is the initial field strength and  $\tau_{d,i} = (AB_i^\alpha)^{-1}$ . Dall’Osso et al. (2012) show that, to be compatible with the observations of magnetar candidates, the magnetic field should decay on a timescale of  $\sim 10^3$  yr for  $B \sim 10^{15}$  G, with a decay index most likely within



the range  $1.5 \lesssim \alpha \lesssim 1.8$ . Here we adopt the initial magnetic field as  $7 \times 10^{14}$ ,  $3 \times 10^{14}$  and  $10^{14}$  G, with  $\alpha = 1.6$  and  $\tau_{d,i} = 10^3/B_{i,15}^\alpha$  yr where  $B_{i,15} = B_i/10^{15}$  G.

On the other hand, the observed braking indices for several young radio pulsars have been measured and are all less than 3 (Lyne et al. 1993, 1996; Kaspi et al. 1994; Livingstone et al. 2005, 2006; Livingstone & Kaspi 2011; Weltevrede et al. 2011), suggesting that the NS magnetic fields may be increasing. In particular, the braking index of the high-field ( $5 \times 10^{13}$  G) radio pulsar PSR J1734–3333 was found to be  $0.9 \pm 0.2$  (Espinoza et al. 2011), implying that this pulsar may soon have the rotational properties of a magnetar. In the second approach, we adopt a field growth model in the following form

$$B = B_i(1 + t/\tau)^\alpha, \quad (18)$$

with  $B_i = 3 \times 10^{12}$  G,  $\tau = 10^3$  yr, and  $\alpha = 1.45$ , so that  $B = 8.5 \times 10^{13}$  G and  $6.3 \times 10^{14}$  G at  $t = 10^4$  and  $4 \times 10^4$  yr, respectively.

In Figure 1 we show the model evolution of the magnetic fields.

#### 4. Spin evolution

A newborn NS is usually rotating rapidly. However, Haberl et al. (2012) suggested that SXP 1062 could have been born with a period much larger than 0.01 s. Some central compact objects (CCOs) in supernova remnants which have spin periods ranging from  $\sim 0.1$  to  $\sim 0.5$  s (Zavlin et al. 2000; Gotthelf et al. 2005; Gotthelf & Halpern 2009) seem to support this point of view, since there is evidence that the spin periods of these sources are very close to the initial ones. Thus in our model we take 0.01 s, 0.5 s and 6.5 s as the initial period of the NS in order to examine whether it can significantly influence the spin-down evolution. We use the ultra-long initial spin period of 6.5 s because this value is larger than  $P_{ej}$  with  $B = 7 \times 10^{14}$  G in the ejector phase, so that the NS will directly enter the supersonic propeller phase after the SN event.

It was shown by Arons & Lea (1976) and Elsner & Lamb (1977) that, for stable accretion to occur, the plasma at the base of the NS magnetosphere should become sufficiently cool, so that the magnetospheric boundary is unstable with respect to interchange instabilities. This can be realized only if the spin period of the star exceeds the break period  $P_{br}$ , and the X-ray luminosity is larger than

$$L_{cr} = 3 \times 10^{36} B_{12}^{1/4} M_{1.4}^{1/2} R_6^{-1/8} \text{ ergs}^{-1}. \quad (19)$$

If  $B \gtrsim 10^{14}$  G, SXP 1062 should be in the subsonic propeller phase. However, it is not clear whether the picture of the subsonic propeller can be applied to BeXBs, due to the

following reasons. (1) The mass accretion in BeXBs is now believed to be triggered by Roche-lobe overflow of the Be discs which is truncated by the NS through a tidal torque (Okazaki & Negueruela 2001; Okazaki et al. 2002; Reig 2011), thus is deviated from the traditional Bondi accretion in supergiant HMXBs. This means that the NS in SXP 1062 is probably surrounded by a (quasi-)disc rather a quasi-static, spherical atmosphere. (2) Even in the spherical wind-fed case, the spin period - orbital period correlation in BeXBs seems to be well accounted for by assuming that the NSs are spinning at the equilibrium periods described by Eq. (3) (Corbet 1984; Waters & van Kerkwijk 1989)<sup>1</sup>. Thus in our calculations we don't consider the subsonic propeller phase, and assume that the evolutionary sequence of the NS is ejector-supersonic propeller-accretor. We use different  $\gamma$  to calculate the spin-down torque in the supersonic propeller phase, and take the equilibrium period (Eq. [3]) as the final period (i.e., the period does not change during the accretor phase unless the magnetic field changes).

In Figures 2 – 4 we show the calculated results corresponding to different initial spin periods of the NS. Here we take the NS mass to be  $M = 1.4M_{\odot}$ , the inclination angle  $\alpha = 90^{\circ}$ ,  $I = 10^{45} \text{ g s}^{-1}$ , and  $R = 10^6 \text{ cm}$ . The relative wind velocity  $V$  is set to be  $300 \text{ km s}^{-1}$ , and the accretion rate is fixed to be  $10^{16} \text{ g s}^{-1}$ . The three thin lines (from top to bottom) describe the spin evolution with initial magnetic field of  $7 \times 10^{14} \text{ G}$ ,  $3 \times 10^{14} \text{ G}$ , and  $10^{14} \text{ G}$  undergoing field decay, respectively; the thick line is for the field growth model with initial field of  $3 \times 10^{12} \text{ G}$ . The solid, dashed, and dotted lines represent the ejector, propeller, and accretor phases, respectively.

We notice that the time spent in the supersonic propeller phase is sensitive to the value of  $\gamma$  which reflect different spin-down mechanisms in the supersonic propeller phase as we mentioned before. In the case of  $\gamma = -1$ , where the spin-down torque is most inefficient, the NS has not evolved out of the supersonic propeller phase at the age of the SNR, even with a superstrong magnetic field. Our results are not sensitive to the initial spin period of the NS. Thus even for the case of ultra-long initial spin period there is no significant change in the final NS period.

In other cases the NS can successfully reach  $P_{\text{eq}}$  when  $t = 10 - 40 \text{ kyr}$ . Since  $P_{\text{eq}}$  depends on the magnetic field, we can see that the magnetic field determines the final spin period which the NS can achieve, and the value of  $\gamma$  determines the evolutionary timescale. In the field decay model, the spin period remains invariant once it reaches  $P_{\text{eq}}$ , since we

---

<sup>1</sup> Additionally, population synthesis calculations by Dai & Li (2006) showed that the distribution of the spin and orbital periods of X-ray pulsars in supergiant HMXBs can be roughly explained without requiring that an X-ray pulsar emerges after the subsonic propeller phase (see also Stella et al. 1986).

assume that during the accretor phase the long-term, net torque from the wind is small. In the field growth model, the spin period keeps increasing with  $P_{\text{eq}}$  in the final stage, since the increase of  $B$  always breaks the instantaneous equilibrium and causes a spin-down torque. It is seen that  $B \gtrsim 10^{14}$  G can fulfill the requirement of SXP 1062 in both models. This result favors that in the supersonic propeller phase matter is ejected at  $R_{\text{m}}$  with the escape velocity under angular momentum conservation, consistent with the numerical calculation by Wang & Robertson (1985).

## 5. Discussion and conclusion

The newly found Be/X-ray binary SXP 1062 is believed to be the first X-ray pulsar associated with a SNR, which shows a combination of young age and long spin period that cannot be explained by a typical NS. Previous studies (Haberl et al. 2012; Popov & Turolla 2012) explored its possible origin invoking initially long spin period or ultra-strong magnetic field. Here we discuss the possibility that SXP 1062 is an accreting magnetar with  $B \gtrsim 10^{14}$  G, and examine in this case how the properties of the NS (i.e. initial spin period, magnetic field and its evolution) and the spin-down torques can be constrained.

Other candidates of accreting magnetars in binaries include 4U 2206+54 (Finger et al. 2010; Reig et al. 2012) and GX 301–2 (Doroshenko et al. 2010). However, it is controversial whether they really possess ultra-strong magnetic fields. Wang (2010) reported the existence of two cyclotron absorption lines at  $\sim 30$  and  $60$  keV in 4U 2206+54, and derived a magnetic field of  $3.3 \times 10^{12}$  G, although no sign of this feature has been detected in other observations. Observations of La Barbera et al. (2005) showed the cyclotron resonance scattering feature at  $\sim 35$ – $45$  keV in GX 301–2, suggesting the field strength of  $4 \times 10^{12}$  G. Ikhsanov & Finger (2012) proposed a magnetic wind accretion model for GX 301–2 to account for the difference in the field strengths derived from the cyclotron lines and from the spin-down rates. In the case of SXP 1062, it is found that the magnetic field may be at least strong as  $\sim B_{\text{Q}}$  in the model of Ikhsanov (2012). For a dipole magnetic field of  $\sim 10^{14}$  G, the electron cyclotron line would appear at  $E > 1$  MeV, but a proton cyclotron line would appear at  $E \sim 0.5(B/10^{14}\text{G}) = 0.3$  keV. Although a line with this energy should be observable with *XMM-Newton* detectors, it is in a region affected by strong interstellar absorption (Reig et al. 2012). Currently, no significant lines have been detected in the persistent emission of magnetars (Mereghetti 2008).

If SXP 1062 is or has been a magnetar, the association between the SNR and SXP 1062 may provide an opportunity to investigate the formation and evolution of magnetars. Vink & Kuiper (2006) showed that there is no evidence that magnetars are formed from

rapidly rotating proto-neutron stars. The SNR associated with SXP 1062 is one of the faintest SNRs known in the SMC (Filipović et al. 2005, 2008; Owen et al. 2011). This seems to be in line with the finding of Vink & Kuiper (2006) that their formation may not be accompanied with extraordinarily bright supernovae. However, it is known that the brightness of SNRs depends strongly on the density of the environment. Nevertheless, the age of the SNR can be used to set useful constraints on the timescale of magnetic field evolution, either due to field decay or growth.

Since the long spin period is most likely to be reached during the propeller phase, the age of the SNR also plays a role in testing the efficiency of the spin-down torques in different propeller mechanisms. Our results seem to rule out the model with  $\gamma = -1$ , and prefer larger values of  $\gamma$  which correspond to more efficient propeller spin-down. Recent 2- and 3-dimensional magnetohydrodynamic (MHD) simulations by Romanova et al. (2005) and Ustyugova et al. (2006) on disc-fed NSs suggest  $\dot{\Omega} \propto -\Omega^2$  for propeller-driven outflows. Toropina et al. (2010) investigate the spinning-down of magnetars rotating in the propeller regime with axisymmetric MHD simulations, and find  $\dot{\Omega} \propto -\Omega^{1.5}$ . It should be noted that the mass transfer rate is assumed to be constant throughout our calculations, but in reality it must have varied with the orbital motion of the NS. For instance, an eccentric orbit may result in alternation among the ejector, propeller and accretor phases. The sporadic outburst behavior will further complicate the spin-down evolution of the NS. This means that the calculated evolutionary sequence in our model and the values of  $\gamma$  should be taken as an illustration and lower limits, respectively. However, both the high spin-down rate and the young age of SXP 1062 provide strong evidence that the binary indeed harbors or harbored a magnetar, and an effective spin-down mechanism is required. We expect further observations to confirm the long-term spin behavior of SXP 1062.

We thank an anonymous referee for helpful comments. This work was supported by the Natural Science Foundation of China under grant number 11133001 and the Ministry of Science, the National Basic Research Program of China (973 Program 2009CB824800), and the Qinglan project of Jiangsu Province.

## REFERENCES

- Aly, J. J. 1985, *A&A*, 143, 19
- Arons, J., & Lea, S. M. 1976, *ApJ*, 207, 914
- Anzer, U. & Börner, G. 1995, *A&A*, 299, 62

- Bildsten, L. et al. 1997, *ApJS*, 113, 367
- Bisnovatyi-Kogan, G. S. 1991, *A&A*, 245, 528
- Corbet, R. H. D. 1984, *A&A*, 141, 91
- Dai, H.-L. & Li, X.-D., 2006, *ApJ*, 653, 1410
- Dall’Osso, S., Granot, J., & Piran, T. 2012, *MNRAS*, 422, 2878
- Davidson, K. & Ostriker, J. P. 1973, *ApJ*, 179, 585
- Davies, R. E., Fabian, A. C., & Pringle, J. E. 1979, *MNRAS*, 186, 779
- Davies, R. E. & Pringle, J. E. 1981, *MNRAS*, 196, 209
- Doroshenko, V., Santangelo, A., & Suleimanov, V. et al. 2010, *A&A*, 515, 10
- Elsner, R. F. & Lamb, F. K. 1977, *ApJ*, 215, 897
- Espinoza, C. M., Lyne, A. G., Kramer, M., Manchester, R. N. & Kaspi, V. 2011, *ApJ*, 741, L13
- Finger, M. H., Ikhsanov, N. R., Wilson-Hodge, C. A., & Patel, S. K. 2010, *ApJ*, 709, 1249
- Filipović, M. D., Haberl, F., & Winkler, P. F., et al. 2008, *A&A*, 485, 63
- Filipović, M. D., Payne, J. L., & Reid, W. et al. 2005, *MNRAS*, 364, 217
- Francischelli, G. J. & Wijers, R. A. M. J. 2002, *ApJ*, 565, 471
- Fryxell, B. A. & Taam, R. E. 1988, *ApJ*, 335, 862
- Gotthelf, E. V. & Halpern, J. P., 2009, *ApJ*, 695, L35
- Gotthelf, E. V., Halpern, J. P., & Seward F. D. 2005, *ApJ*, 627, 390
- Harbel, F., Filipović, M. D., & Pietsch, W. et al. 2000, *A&AS*, 142, 41
- Harbel, F., Sturm, R., & Filipović, M. D. et al. 2012, *A&A*, 537, L1
- Hénault-Brunet, V., Oskinova, L. M., & Guerrero, M. A. et al. 2012, *MNRAS*, 420, L13
- Ikhsanov, N.R. 2001, *A&A*, 368, L5
- Ikhsanov, N.R. 2012, *MNRAS*, 424, L39

- Ikhsanov, N. R. & Finger, M. H. 2012, *ApJ*, 753, 1
- Illarionov, A. F. & Kompaneets, D. 1990, *MNRAS*, 247, 219
- Illarionov, A. F. & Sunyaev, R. A. 1975, *A&A*, 39, 185
- Kaspi, V. M., Manchester, R. N., Siegman, B., Johnston, S., & Lyne, A. G. 1994, *ApJ*, 422, L83
- La Barbera, A., Segreto, A., & Santangelo, A., et al. 2005, *A&A*, 438, 617
- Lipunov, V. M. 1982, *Soviet Astronomy*, 26, 537
- Lipunov, V. M., 1992, *Astrophysics of Neutron Stars*, Berlin, Springer-Verlag
- Livingstone, M. A. & Kaspi, V. M. 2011, *ApJ*, 742, 31
- Livingstone, M. A., Kaspi, V. M., & Gavriil, F. P. 2005, *ApJ*, 633, 1095
- Livingstone, M. A., Kaspi, V. M., Gotthelf, E. V., & Kuiper, L. 2006, *ApJ*, 647, 1286
- Lynden-Bell, D. & Pringle, J. E. 1974, *MNRAS*, 168, 603
- Lyne, A. G., Pritchard, R. S., & Smith, F. G. 1993, *MNRAS*, 265, 1003
- Lyne, A. G., Pritchard, R. S., Graham-Smith, F., & Camilo, F. 1996, *Nature*, 381, 497
- Matsuda, T., Ishii, T., & Sekino, N. et al. 1992, *MNRAS*, 255, 183
- Mereghetti, S. 2008, *A&A Rev.*, 15, 225
- Mori, K. & Ruderman, M. A. 2003, *ApJ*, 592, L75
- Okazaki, A. T., Bate, M. R., Ogilvie, G. I., & Pringle, J. E. 2002, *MNRAS*, 337, 967
- Okazaki, A. T. & Negueruela, I. 2001, *A&A*, 377, 161
- Owen, R. A., Filipović, M. D., & Ballet, J., et al. 2011, *A&A*, 530, A132
- Popov, S. B. & Turolla, R. 2012, *MNRAS*, 421, L127
- Raguzova N. V. & Lipunov V. N. 1998, *A&A*, 340, 85
- Reig, P. 2011, *Ap&SS*, 321, 1
- Reig, P., Torrejón, J. M., & Blay, P. 2012, *MNRAS*, in press (arXiv:1203.1490)

- Romanova, M. M., Ustyugova, G. V. Koleoba, A. V., & Lovelace, R. V. E., 2005, ApJ, 635, L165
- Ruffert, M. 1999, A&A, 346, 861
- Shakura, N. I. 1975, Sov. Astron. Lett., 1, 223
- Shakura, N., Postnov K., & Kochetkova A. et al. 2012, MNRAS, 420, 216
- Spitkovsky, A. 2006, ApJ, 648, L51
- Stella, L., White, N. E., & Rosner, R. 1986, ApJ, 308, 669
- Toropina, O., Romanova, M., & Lovelace, R. V. E. 2010, in Proceedings of the 25th Texas Symposium on Relativistic Astrophysics. December 6-10, 2010. Heidelberg, Germany. Eds. F. M. Rieger, C. van Eldik and W. Hofmann. Published online at <http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=123>, id.232
- Ustyugova, G. V., Koleoba, A. V., Romanova, M.M., & Lovelace, R. V. E. 2006, ApJ, 646, 304
- Vink, J. & Kuiper, L. 2006, MNRAS, 370, L14
- Wang, W., 2010, A&A, 520, A22
- Wang, Y.-M. 1995, ApJ, 449, L153
- Wang, Y.-M. & Robertson, J. A. 1985, A&A, 151, 361
- Weltevrede, P., Johnston, S., & Espinoza, C. M. 2011, MNRAS, 411, 1917
- Waters, L. B. F. M. & van Kerkwijk, M. H. 1989, A&A, 223, 296
- Yokogawa, J., Imanishi, K., & Tsujimoto, M. et al. 2003, PASJ, 55, 161
- Zavlin, V. E., Pavlov, G. G., Sanwal, D., & Trumper, J., 2000, ApJ, 540, L25

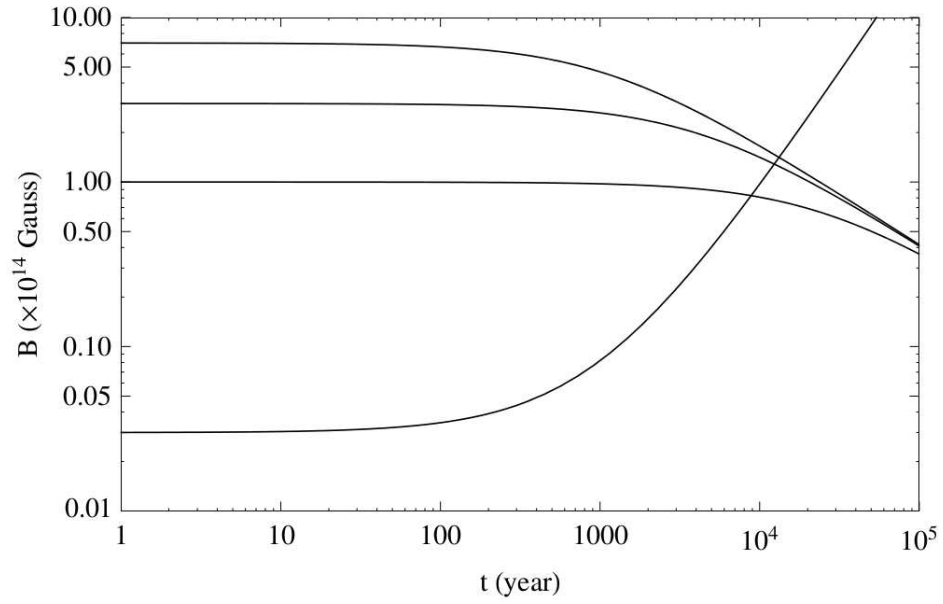


Fig. 1.— Evolution of the NS magnetic fields in different models.



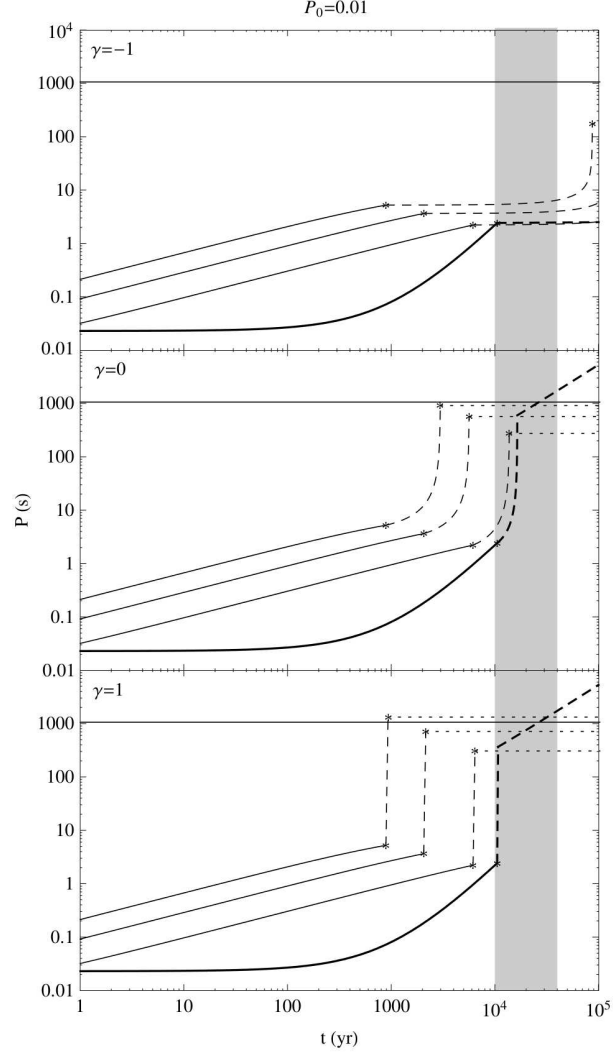


Fig. 2.— The spin-down evolution for a NS with a 0.01 s initial spin period. In this and following figures, solid, dashed and dotted lines represent the ejector, supersonic propeller and accretor phases, respectively. Symbol \* represents the transition of evolutionary stages. The shaded area and the horizontal line mark the age and the spin period of SXP 1062 respectively. From the top to the bottom, the initial magnetic field is  $B_i = 7 \times 10^{14}$  G,  $3 \times 10^{14}$  G,  $10^{14}$  G, and  $3 \times 10^{12}$  G.

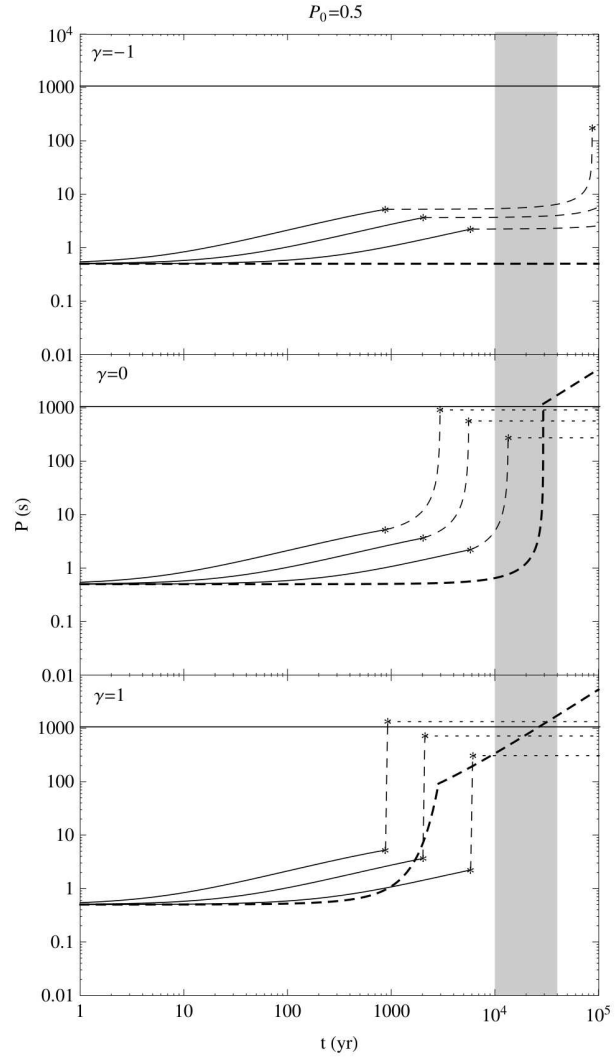


Fig. 3.— The spin-down evolution for a NS with a 0.5 s initial spin period. Other parameters are similar to in Figure 2.

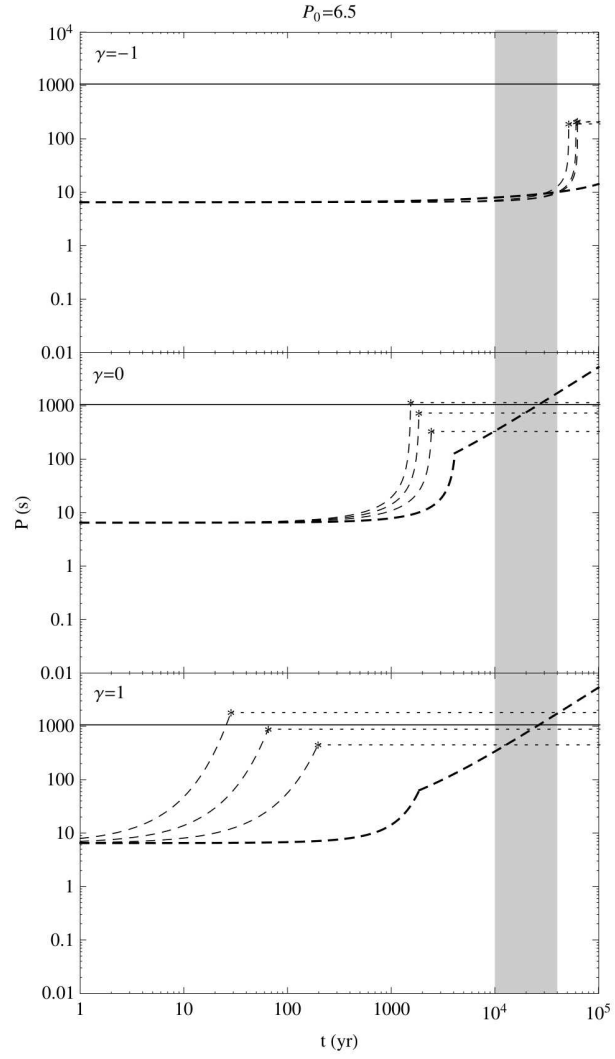


Fig. 4.— The spin-down evolution for a NS with a 6.5 s initial spin period. Other parameters are similar to in Figure 2.